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Flood Control Structures Research Program

Open-Channel Velocity Prediction Using STREMR Model

by Stephen T. Maynord

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Prepared for Headquarters, U.S. Army Corps of Engineers

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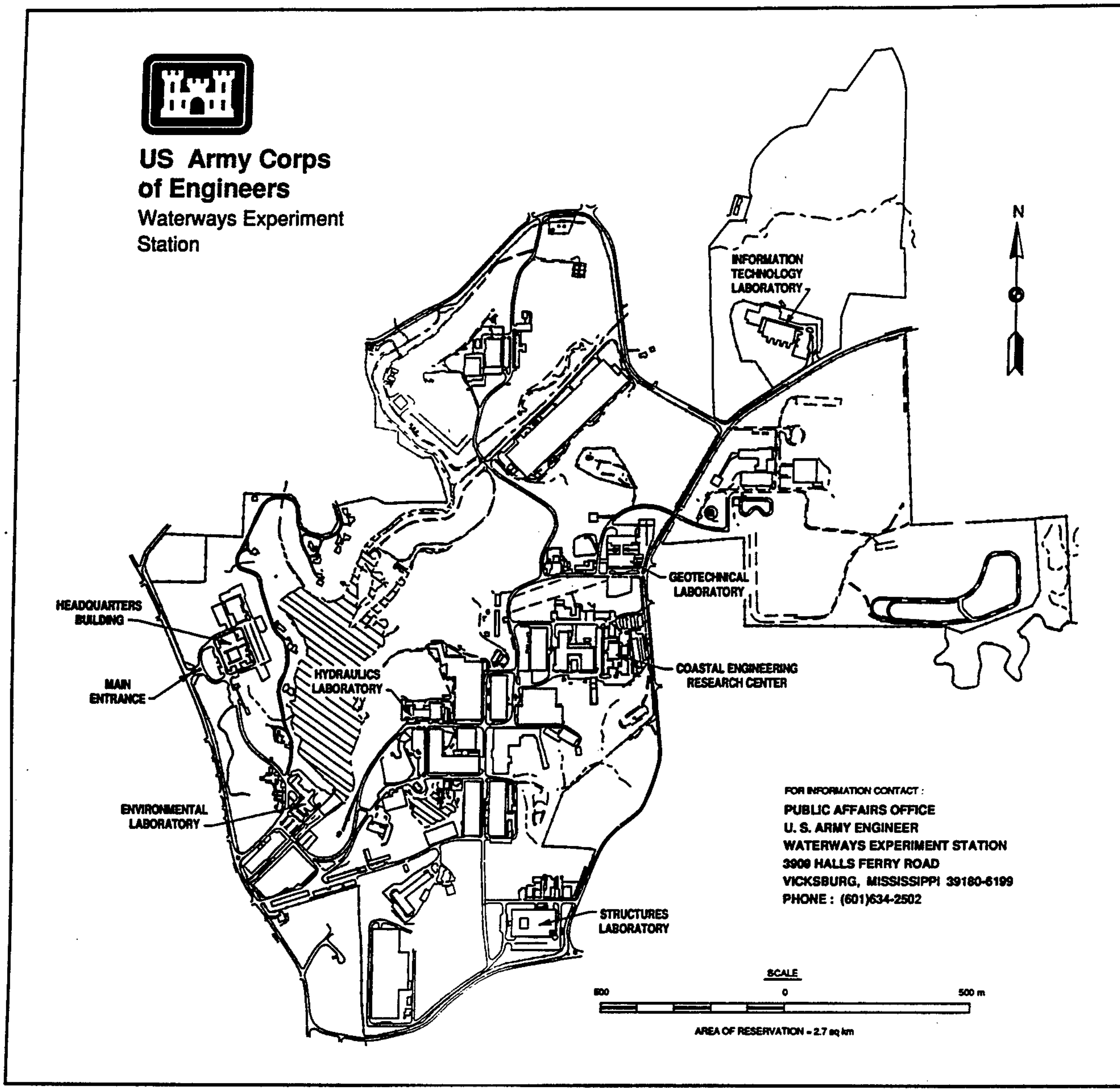

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Contents

Preface

The work described in this report was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Flood Control Structures Research Program under Civil Works Investigation, "Riprap Toe and End Section Design." HQUSACE Program Monitor was Mr. Tom Munsey.

The work was performed by personnel of the Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station (WES), during 1994-1995. The study was accomplished under the direction of Mr. Frank A. Herrmann, Jr., Director, Hydraulics Laboratory (HL); Mr. Richard A. Sager, Assistant Director, HL; and Dr. Larry L. Daggett, Acting Chief of the Navigation Division (HN), HL. The study was conducted by Dr. S. T. Maynord of the Navigation Effects Group, HN. This report was written by Dr. Maynord.

At the time of publication the Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce Howard, EN.

1 Introduction

STREMR Model

The STREMR model is a two-dimensional numerical model for depth-averaged incompressible flow developed and described in Bernard and Schneider (1992) and Bernard (1993). STREMR accommodates the following: irregular boundaries, nonuniform bathymetry, and empirical corrections for turbulence and secondary flow. STREMR uses a rigid-lid surface approximation and a finite-volume scheme to discretize and solve the governing equations for primary flow, secondary flow, and turbulence energy and dissipation rate. The turbulence equations are taken from the standard κ-ϵ turbulence model. The STREMR model was selected for this comparison because Bernard and Schneider (1992) have shown that the empirical correction for secondary flow significantly improves the prediction of velocities in channel bends. All runs of the STREMR model were conducted with (a) the default values of all parameters and coefficients, (b) the turbulence model on, and (c) no attempt to adjust roughness coefficients or any other input values to improve agreement between computed and measured data. Comparative runs at the beginning of this study showed that 8 cells are adequate (but possibly not the minimum) to resolve velocities on the side slope. More than 8 cells on the side slope resulted in no change in the velocity distribution. Cell aspect ratios (length/width) ranged from 5.0 to 8.3. For a trapezoidal channel with a straight approach, a single bend, and a straight exit, 3 hours were required to generate a grid and run the model on a 486 personal computer (66 MHz). Natural channels required much longer due to the variable bathymetry along the length of the channel.

Purpose

Two-dimensional depth-averaged models are widely used in hydraulic engineering for solving open-channel flow problems. These models are often used to predict velocity distributions for a variety of purposes including channel stability, channel protection, sediment transport, and navigation studies. It is essential to assess the quality of these predictions by comparing model velocities to measured velocities.

Scope of Work

This report compares the STREMR two-dimensional depth-averaged model to measured data from five different open channels.

2 Influence of Rigid Lid

STREMR requires the input of water depth along and across the channel since it is a rigid lid model. Depth can come from observed water-surface profiles, computed one-dimensional water-surface profile methods, or physical model observations, as done in this study. In most cases these depths are determined from a single water-surface elevation for a cross section and do not reflect any superelevation that occurs in bends. Does this omission of superelevation have a significant effect on the outer bank velocities, which are the focus of this study? Two opposing factors may contribute to changes along the outer bank. First, the increased depth along the outer bank will increase the flow area, which should reduce velocities. Second, the increased depth will reduce the relative effect of bottom friction, which should increase velocities. Comparative runs using the 2.9-cu m/sec (101-cfs) discharge in the Riprap Test Facility (RTF)[1] were made to determine the net effect of these opposing factors. The RTF (Figure 1) is an open channel facility with four bendways and a maximum discharge capacity of 5.7 cu m/sec (200 cfs). The cross section is a trapezoidal channel with a 3.6-m (11.9-ft) bottom width and 1V:2H side slopes. Only the first bend of the RTF, a 45.7-m (150-ft) straight approach channel, and a 21.9-m (72-ft) straight exit channel were simulated in the STREMR model. The Manning's n used in all cells was 0.027, which represented the riprap that covered the bottom and side slopes and had a maximum, average, and minimum size of 53.3, 35.6, and 15.2 mm (2.1, 1.4, and 0.6 in.), respectively. The grid used to simulate the 2.9-cu m/sec (101-cfs) discharge had 8 cells representing each side slope and 20 cells representing the channel bottom. Longitudinally, the grid had 50 cells representing the approach channel, 26 cells representing the bend, and 24 cells representing the exit channel. Average flow depth along the length of the RTF for the 2.9-cu m/sec (101-cfs) discharge was 0.6 m (2.11 ft).

The rigid lid comparisons were run with the secondary current modification "Bender" activated. The first run was conducted with a lid providing a constant depth of 0.6 m (2.11 ft) over the channel bottom with no superelevation across the channel. Output from the first run defined the pressure on the lid across the channel, which was used to reposition the lid to reflect the superelevation in the bend. The maximum superelevation (defined as inside

[1] For convenience, symbols and abbreviations are listed in the notation (Appendix A).

elevation - outside elevation) from STREMR was 30.5 mm (0.10 ft) which agreed well with the maximum observed superelevation from the RTF and from the superelevation Δh calculated from Chow (1959) using

$$\Delta h = \frac{V_{avg}^2 W}{gR} \tag{1}$$

where

V_{avg} = average channel velocity

W = water-surface width

g = gravitational acceleration

R = center-line radius of the bend

STREMR was rerun with the altered lid. Velocity along the outer bank increased most at the cell at the water's edge where the depth change between conditions with superelevation and without superelevation was most significant. The outer bank cell at station 2+63 experienced the largest increase in velocity of 8.3 percent while experiencing a 48 percent increase in depth with superelevation. As a general rule, the percent increase in velocity was less than or equal to 20 percent of the increase in depth along the outer bank. At halfway up the outer bank side slope at station 2+63, the increase in depth was about 6 percent and the increase in velocity was about 1 percent. In this case, where the maximum superelevation is about 6 percent of the mean channel depth, the effects of omitting superelevation are negligible. Effects are most significant on the upper part of the side slope where a later portion of this study shows the numerical model to overestimate velocity without including superelevation. Including superelevation will only make the upper bank prediction worse. The comparisons with observed data in Chapter 3 were conducted without superelevation.

3 Comparisons with Observed Data

Riprap Test Facility, Trapezoidal Channel

Details of the RTF are given in Chapter 2, and the velocities used in this comparison are provided in Maynord (1992). Bernard and Schneider (1992) compared velocities from the STREMR model to velocities measured in the RTF at a discharge of 1.4 cu m/sec (49.5 cfs). Velocities measured at discharges of 2.9 and 4.2 cu m/sec (101 and 150 cfs) are used in this report. Stations 1+78, 2+81, and 3+06 are used in the comparison. Measured and computed velocities for a discharge of 2.9 cu m/sec (101 cfs) are shown in Figure 2. STREMR runs both with and without Bender activated are shown at stations 2+81 and 3+06.

The grid used to simulate the 4.2-cu m/sec (150-cfs) discharge had 8 cells representing each side slope and 18 cells representing the channel bottom. The same longitudinal cell spacing used for 2.9 cu m/sec (101 cfs) was used for 4.2 cu m/sec (150 cfs). Flow depth for the 4.2-cu m/sec (150-cfs) discharge was 0.8 m (2.58 ft). Measured and computed velocities for a discharge of 4.2 cu m/sec (150 cfs) are shown in Figure 3. Also shown at stations 1+78 and 2+81 are results from Abraham (1991) showing predictions from the RMA-2 model, which uses a finite element solution to the flow field and has no empirical correction for secondary currents. The RMA-2 grid was much coarser on the side slopes than used herein; therefore, a comparison of side slope velocities is not valid.

Detailed side slope velocities at station 2+81 in the RTF were reported in Maynord (1992) and plotted in Figures 4 and 5 for side slopes of 1V:2H and 1V:3H, respectively. Velocities were measured with a pitot tube; also, the vertical velocity profile was integrated to obtain the depth-averaged velocity. Velocities are plotted in a dimensionless fashion as the ratio of depth-averaged velocity V to average channel velocity. Measured data represent discharges of 1.7. 1.8, and 1.9 cu m/sec (60, 65, and 70 cfs). Also shown in Figures 4 and 5, with a solid line, are the computed velocity ratios for a STREMR run at 1.8 cu m/sec (65 cfs).

0.5-Rad (30-Deg) Bend, Trapezoidal Channel

A trapezoidal channel with a 0.5-rad (30-deg) bend angle, 1.5-m (5-ft) bottom width, 1V:2H side slopes, and 0.003 ft/ft bottom slope was tested at a 0.6-cu m/sec (20-cfs) discharge and a 0.3-m (0.97-ft) depth. Velocities were measured with a pitot tube, and the vertical profile was integrated to obtain the depth-averaged velocity. The grid used in the STREMR model had 8 cells on each side slope and 20 cells on the channel bottom. Longitudinally, the approach channel had 25 cells, the bend had 6 cells, and the exit reach had 8 cells. Manning's n for all cells was 0.021, which represented the 9.4- to 12.7-mm (3/8- to 1/2-in.) crushed limestone covering the channel. The channel schematic is shown in Figure 6; the measured velocities versus computed velocities are shown in Figure 7.

1.7-Rad (100-Deg) Bend, Trapezoidal Channel

A trapezoidal channel with a 1.7-rad (100-deg) bend angle, 1.3-m (4.4-ft) bottom width, 1V:2H side slopes, and 0.0025 ft/ft bottom slope was tested at both a 0.15-cu-m/sec- (5.3-cfs-) discharge with a 152-mm (0.50-ft) depth and at a 0.16-cu-m/sec (5.5-cfs) discharge with a 158-mm (0.52-ft) depth. Velocities were measured with a pitot tube, and the vertical profile was integrated to obtain the depth-averaged velocity. The grid used in the STREMR model had 8 cells on each side slope and 24 cells on the channel bottom. Longitudinally, the 6-m- (20-ft-) long approach channel had 20 cells, the bend had 50 cells, and the 4.6-m- (15-ft-) long exit reach had 15 cells. Manning's n for all cells was 0.021, which represented the 5.1- to 12.7-mm (0.2- to 0.5-in.) crushed limestone covering the channel. The channel schematic and the ratio of measured velocity/average channel velocity are shown in Figures 8 and 9; the measured velocities versus computed velocities are shown in Figure 10 for stations 63.9, 69.9, and 96.3.

3.1-Rad (180-Deg) Bend, Natural Channel

A moveable sand bed channel with fixed, smooth banks, a 3.1-rad (180-deg) bend angle, 2.4-m (8.0-ft) water-surface width, and 1V:1.5H side slopes was tested at 0.2-cu-m/sec (5.45-cfs) discharge (Odgaard and Kennedy 1982). Velocities were measured with a miniature propeller current meter. The channel was allowed to form a typical point bar with scoured outer bank toe configuration before the velocities were measured. Since the quality of the STREMR prediction is strongly dependent on the quality of available bathymetric data, this natural channel presents a particular problem in a changing bathymetry all along the channel. Detailed bathymetric data were available only at stations 64, 80, 88, 96, 112, and 144 shown in Figure 11. Bathymetry upstream of station 64 and downstream of station 144 was developed from a contour map that was not as accurate as the section data.

This lack of detailed data is typical of natural channel applications. The grid used in the STREMR model had 40 uniformly spaced cells across the width of the channel. Longitudinally, the 7.6-m- (25-ft) long approach channel had 25 cells, the bend had 70 cells, and the 1.5-m- (5-ft-) long exit reach had 5 cells. Manning's n for all cells on the smooth side slope was 0.010. Manning's n value for the channel bottom was determined to be 0.0235 based on the slope of the water-surface profiles presented in Odgaard and Kennedy (1982) and considering the portion of the wetted perimeter of each surface. Measured versus computed velocities are shown in Figure 12. Note that the computed profile without the secondary current correction is closer to the observed data than in the trapezoidal channels. It appears that bathymetry in natural channels plays a significant and possibly dominant role in defining velocity distribution.

Straight Trapezoidal Channel with Varying Side Slope

A straight tilting flume was used to evaluate STREMR for 1V:2H and 1V:3H side slopes. A schematic of the flume is shown in Figure 13. Crushed limestone 12.7 to 19.1 mm (1/2 to 3/4 in.) was used on the channel bottom and side slope. A Manning's n value of 0.0227 was used for both the channel bottom and side slope, and a discharge of 0.1 cu m/sec (2.5 cfs) was used for all tests. A pitot tube was used to measure velocity, and the vertical profile was integrated to obtain the depth-averaged velocity. The grid used in the STREMR model had 20 uniformly spaced cells across the channel bottom and side slope with a 1V:2H side slope and 22 cells for the bottom with a 1V:3H side slope. Longitudinally, 10 cells were used in the rectangular approach channel, 10 cells in the transition, and 30 cells in the side slope section. The smooth, vertical left wall was treated as a slip boundary in the STREMR model. Velocities were measured at 1.5 and 3 m (5 and 10 ft) from the downstream end of the flume and velocities were computed at 2.3 m (7.5 ft) from the downstream end of the flume. Computed velocities versus measured velocities are shown in Figure 14.

4 Analysis of Results

The comparison presented herein is based on physical model velocities that were measured with pitot tubes and propeller velocity meters, which do not measure the flow direction. These meters are oriented so they are in line with the flow direction before the reading is taken. This measured value is compared to the velocity vector magnitude from the STREMR model at the same location. Evaluation of the STREMR model uses physical model data because these data tend to be more reliable than field data since error sources are generally smaller in the laboratory. Total error in these model data is equal to systematic plus repeatability errors. Systematic errors include errors in meter calibration and the computation of depth-averaged velocity from a finite number of velocity readings in the vertical. Based on previous calibration exercises by the author, the systematic errors are felt to be less than or equal to 5 percent. Repeatability errors include errors in setting discharge, horizontal and vertical positioning of velocity meters, and reading of velocity meters, particularly differential manometers. Vertical differential manometers used with pitot tubes in this study can yield significant repeatability errors when differentials are low, which occurs when velocities are less than 0.5 m/sec (1.5 ft/sec). This can explain much of the difference between the two sets of readings in Figure 10. The higher velocity magnitudes in the RTF data in Figures 4 and 5 were also taken with a vertical manometer pitot tube but have much less scatter. Based on comparisons of discharge computed from measured velocities integrated over a cross section to discharge measured from a meter, and variability of multiple velocity readings taken at the same point, it is the author's opinion that the repeatability error for the velocities used in this investigation is generally within 5 percent and almost always within 10 percent of the actual velocity. The higher percentage is applicable to the 0.5-rad (30-deg) bend, 1.7-rad (100-deg) bend, and the straight channel where a pitot tube was used to measure low velocities. The lower percentage is applicable to data from the RTF. Thus, total error for the physical model data used herein is generally within 10 to 15 percent.

From the plots of observed data versus computed data, it is obvious that the STREMR model is in significant error in trapezoidal channel bendways without the secondary current correction. In Figure 3, the RMA-2 depth-averaged model exhibits the same error. To evaluate the predictions from the

STREMR model using the secondary current correction, the cross section was divided into three regions designated channel bottom (CB), lower bank (LB), and upper bank (UB). The channel bottom includes all points over the channel bottom except those directly over the slope toe. The lower bank includes all points from the slope toe up to halfway up the bank but not including those exactly halfway up the bank. The upper bank includes all points equal to or above halfway up the bank. Two parameters comparing measured velocities and computed velocities will be used in this analysis of STREMR, one of which is similar to parameters in Willmott (1982). Willmott found that correlation coefficients cannot be used to compare observed data and computed data. Willmott recommends the Mean Absolute Error (MAE) defined as

$$MAE = \frac{\sum |V_c - V_m|}{N} \tag{2}$$

where

V_c = computed velocity from STREMR with the secondary current correction

V_m = measured velocity

N = number of data points

MAE was not used herein because the measure of the error was the same for any magnitude of velocity. Using MAE, a measured velocity of 0.15 m/sec (0.5 ft/sec) and a computed velocity of 0.3 m/sec (1.0 ft/sec) were shown to have the same degree of error as a measured velocity of 1.5 m/sec (5 ft/sec) and a computed velocity of 1.7 m/sec (5.5 ft/sec). This study compared three channel locations with different velocity magnitudes and a relative error measure was needed. The Mean Relative Error (MRE) was used herein and defined as

$$MRE = \sum \frac{\left| \dfrac{V_c - V_m}{V_m} \right|}{N} \tag{3}$$

MRE gives no indication if computed values tend to be higher or lower than measured values. Mean Trend Error (MTE) is defined as

$$MTE = \frac{\sum \frac{V_c - V_m}{V_m}}{N} \tag{4}$$

MTE indicates if V_c tends to be larger (MTE = positive) or smaller (MTE = negative) than V_m. If MRE is low, the model is accurately predicting observed results. If MRE is not low, MTE is used to determine if the numerical model follows a trend of high or low prediction. Results showing MRE and MTE for each channel are shown in Table 1. Scatter plots of the data from the channels with 1V:2H side slopes are shown in Figures 15, 16, and 17 for locations UB, LB, and CB, respectively.

The accuracy of STREMR on side slopes decreases as the waterline is approached and as the side slope angle increases. Based on the comparisons presented herein, STREMR is not recommended for the upper half of side slopes until additional study is conducted in this area. The lack of agreement with observed data could be the result of increased resistance on the side slope and/or problems with the viscosity coming from the turbulence model on the side slope. Limited tests were conducted to see if increased resistance could be used to reduce computed upper bank velocities that were too high. The amount of increase in resistance required to significantly reduce computed velocities was larger than physically reasonable. Additional study of the resistance and viscosities from the turbulence model on side slopes is recommended.

5 Nomographs

The STREMR model was used to develop a nomograph for determining the velocity increase in trapezoidal channel bends. STREMR was used to determine the maximum V_{ss} in a channel bend, where V_{ss} is the depth-averaged velocity at 20 percent of the slope length up from the toe. The average channel velocity was used to normalize V_{ss}, and the ratio V_{ss}/V_{avg} was found to vary with *R/W* and aspect ratio defined as bottom width/maximum depth. The modelling used a depth of 4.6 m (15 ft), 1V:3H side slopes, V_{avg} of 1.8 m/sec (6 ft/sec), Manning's n of 0.038, and the same n on the channel bottom and side slopes. Comparative runs with different side slopes show that the results are valid for 1V:1.5H to 1V:3H. Changes in average channel velocity had no effect on V_{ss}/V_{avg}. The curves were developed for n/(maximum depth)$^{1/6}$ = 0.026 and will be conservative for all values less than 0.026. Cases where the bottom friction to depth ratio is significantly greater than 0.026 should be run with the STREMR model because the higher relative bottom friction will cause higher V_{ss}/V_{avg}. The curves are shown in Figure 18 (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1994).

Note that in Figure 18, the curves are terminated at V_{ss}/V_{avg} = 1.0. This is the recommended procedure in HQUSACE (1994) and is generally a good design practice because channels are rarely straight enough to warrant values less than 1.0. However, there are channels straight enough that have ratios significantly less than 1.0, particularly those having sand bottoms in which the bottom resistance is less than the side slope resistance. A second nomograph was developed for straight trapezoidal channels at least five channel widths from upstream bends or other features that create an imbalance of flow. (HQUSACE (1994) presents a procedure for determining the decay in V_{ss}/V_{avg} downstream of channel bends that is better than the five-channel-width rule of thumb.) V_{ss}/V_{avg} was found to vary with aspect ratio and ratio of bed and bank n. The nomograph (Figure 19) was based on a 1V:2H side slope but can be used for side slopes from 1V:1.5H to 1V:3H. STREMR was based on n/(maximum depth)$^{1/6}$ = 0.023 and will be conservative for all values greater than 0.023. Ratios significantly less than 0.023 should be run with the STREMR model.

6 Discussion of Results and Conclusions

From the plots of observed data versus computed data, Table 1, and the scatter plots, the following conclusions are presented:

a. Without the secondary current correction, the STREMR model should not be used in curved trapezoidal channels. Since the RMA-2 model also does poorly for the curved channel RTF data shown in Figure 3, this conclusion appears applicable to all two-dimensional depth-averaged models not having a secondary current correction.

b. The STREMR model will provide good predictions of velocity over the channel bottom in trapezoidal channels having 1V:2H and 1V:3H side slopes. The MRE was 0.047 and 0.045 for the 1V:2H and 1V:3H side slopes, respectively. The MTE was small for the channel bottom of both 1V:2H and 1V:3H side slopes.

c. The STREMR model will provide good predictions of velocity on the lower half (LB) of 1V:3H side slopes in trapezoidal channels where the MRE is 0.050 and the MTE is small. On the lower half of 1V:2H side slopes in trapezoidal channels, the MTE was small but the MRE was 0.080 indicating a decrease in the model's ability to predict velocity on steeper side slopes.

d. On the upper half (UB) of 1V:2H and 1V:3H side slopes in trapezoidal channels, the STREMR model overpredicts velocity with the MTE of 0.196 and 0.176 for the 1V:2H and 1V:3H side slopes, respectively. As on the LB, the STREMR model tends to do better on the UB of 1V:3H side slopes than on the UB of 1V:2H side slopes.

e. The rigid lid approximation has a negligible influence on velocity on the LB for the superelevations occurring in these test cases. Superelevation can be computed using Equation 1. If 20 percent of the depth change with superelevation is significant on the LB, superelevation should be included in defining the rigid lid.

f. In the 3.1-rad (180-deg) bend with a movable bed typical of natural channels, the channel bottom had a MRE of 0.104 and a MTE of 0.041, which are higher than the values from the channel bottom of the trapezoidal channels. This is likely due to a lack of detailed bathymetry data, which is typical of natural channels, and to a changing resistance coefficient that can occur for different bed forms. The velocity profile without secondary current correction is closer to the observed data because the bathymetry tends to determine and reflect the velocity distribution.

g. As stated in Chapter 1, the goal of this study is to evaluate the STREMR model for determining velocities for use in channel protection. Based on the comparisons presented herein, the STREMR model is recommended for estimating velocity on the channel bottom and the lower half of the channel side slopes in trapezoidal channels. For natural channels, additional data are needed. Since STREMR addresses the mechanics of flow in trapezoidal channels, it is likely the best available tool for natural channels. Natural channel predictions will generally be limited by the lack of detailed bathymetry and resistance data.

h. Nomographs for estimating V_{ss}/V_{avg} were developed using the STREMR model for curved and straight trapezoidal channels.

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Table 1
Comparison of Computed and Measured Velocities

Model	Side Slope	Location	N	MRE	MTE
RTF 101	2	UB	6	0.128	0.102
		LB	18	0.076	-0.003
		CB	15	0.060	0.036
RTF 150	2	UB	6	0.138	0.070
		LB	24	0.109	-0.045
		CB	15	0.047	-0.014
RTF 65	2	UB	7	0.152	0.152
		LB	17	0.047	-0.008
		CB	0	--	--
	3	UB	13	0.185	0.179
		LB	20	0.045	0.006
		CB	5	0.053	-0.053
30DBend	2	UB	2	0.139	0.139
		LB	8	0.094	0.071
		CB	10	0.040	0.028
100DBend	2	UB	24	0.257	0.257
		LB	23	0.060	-0.015
		CB	24	0.040	-0.040
180DBend	1.5	UB	0	--	--
		LB	3	0.060	-0.044
		CB	27	0.104	0.041
Straight	2	UB	2	0.325	0.325
		LB	4	0.157	0.157
		CB	14	0.051	-0.034
	3	UB	6	0.169	0.169
		LB	6	0.068	0.068
		CB	12	0.041	0.041

(Continued)

Note: RTF 101 = model with discharge of 2.9 cu m/sec (101 cfs)
RTF 150 = model with discharge of 4.2 cu m/sec (150 cfs)
RTF 65 = model with discharge of 1.8 cu m/sec (65 cfs)
30DBend = model with 0.5-rad (30-deg) bend
100DBend = model with 1.7-rad (100-deg) bend
180DBend = model with 3.1-rad (180-deg) bend

Table 1 (Concluded)					
Model	**Side Slope**	**Location**	**N**	**MRE**	**MTE**
All Data	2	UB	47	0.208	0.196
		LB	94	0.080	-0.005
		CB	78	0.047	-0.010
	3	UB	19	0.180	0.176
		LB	26	0.050	0.020
		CB	17	0.045	0.026

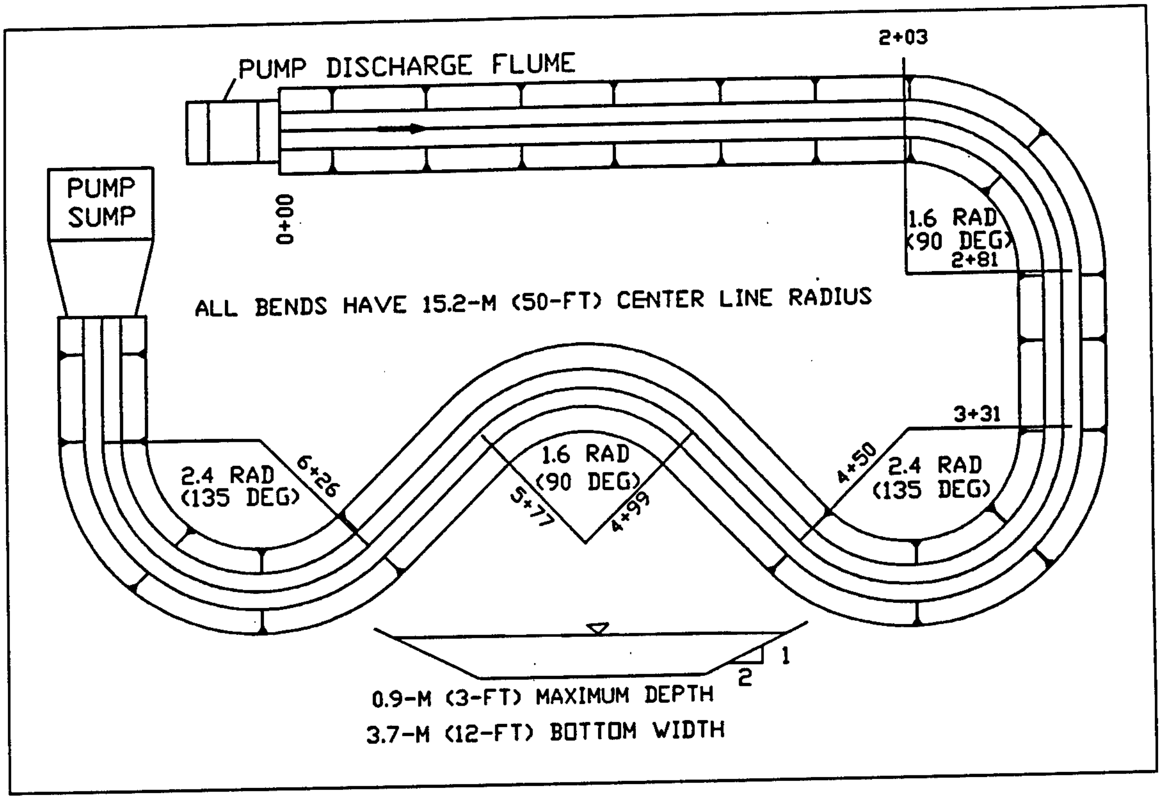


Figure 1. Riprap Test Facility schematic

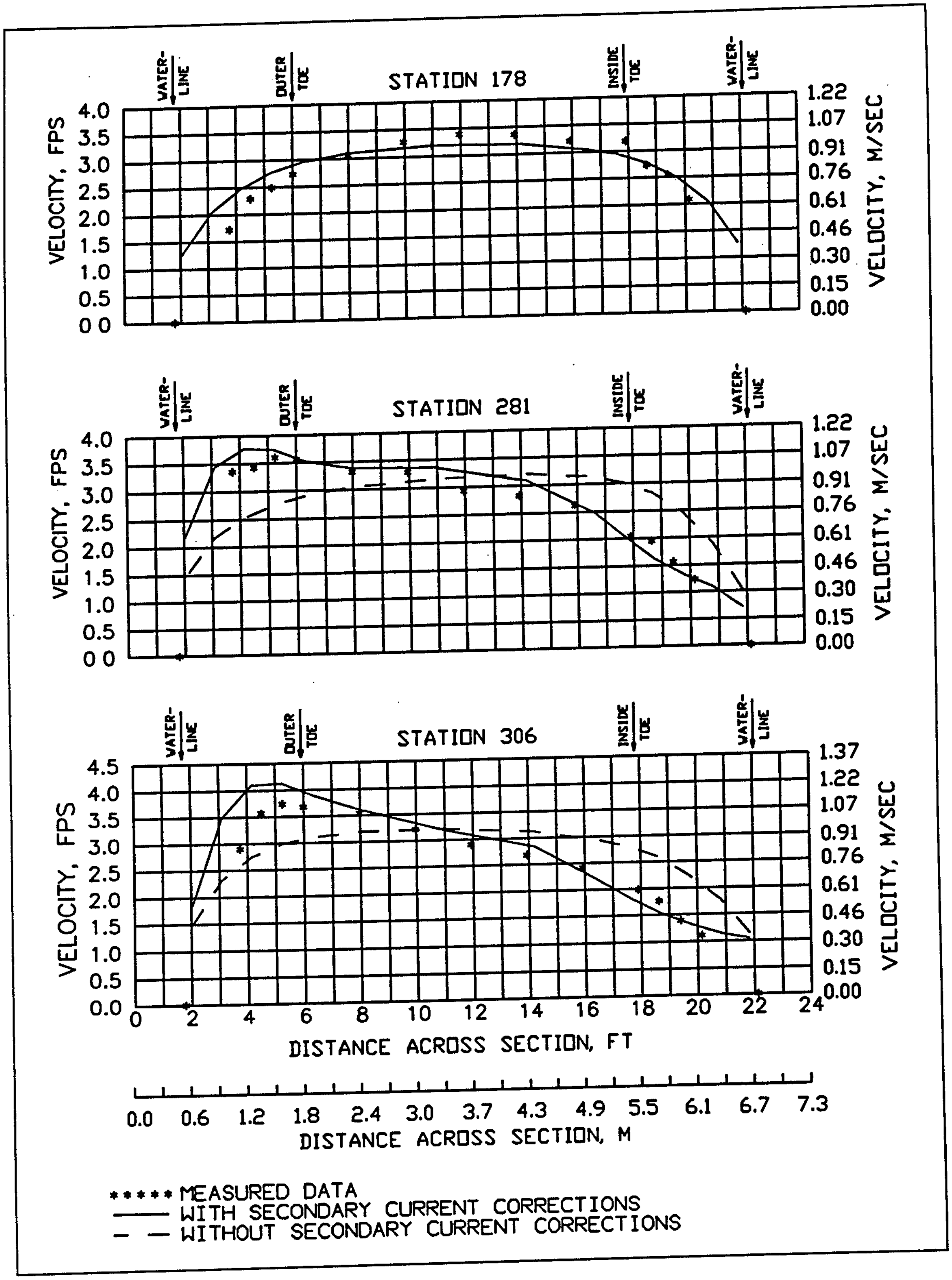


Figure 2. Predicted versus observed velocities, RTF, discharge 2.9 cu m/sec (101 cfs)

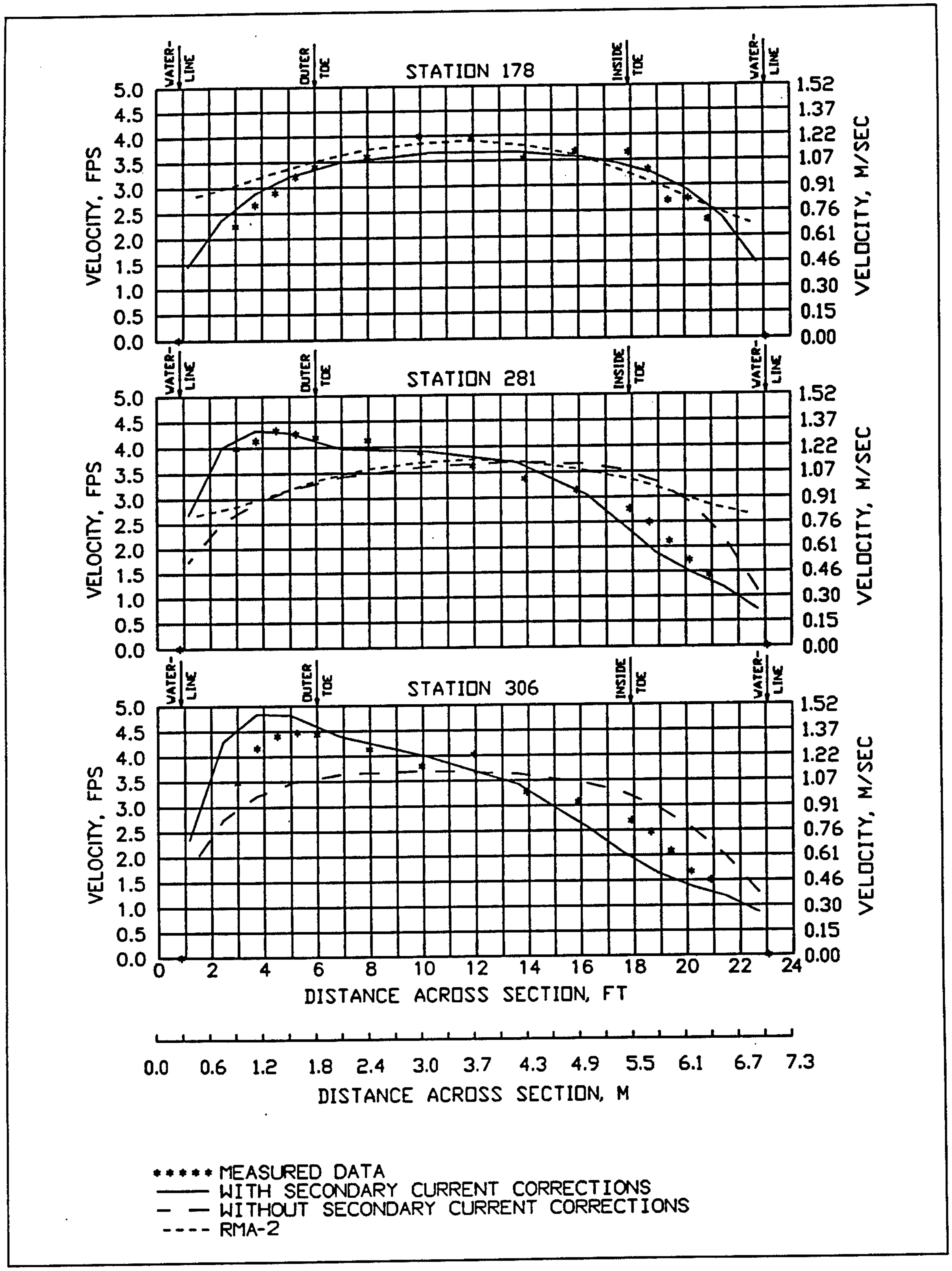


Figure 3. Predicted versus observed velocity, RTF, discharge 4.2 cu m/sec (150 cfs)

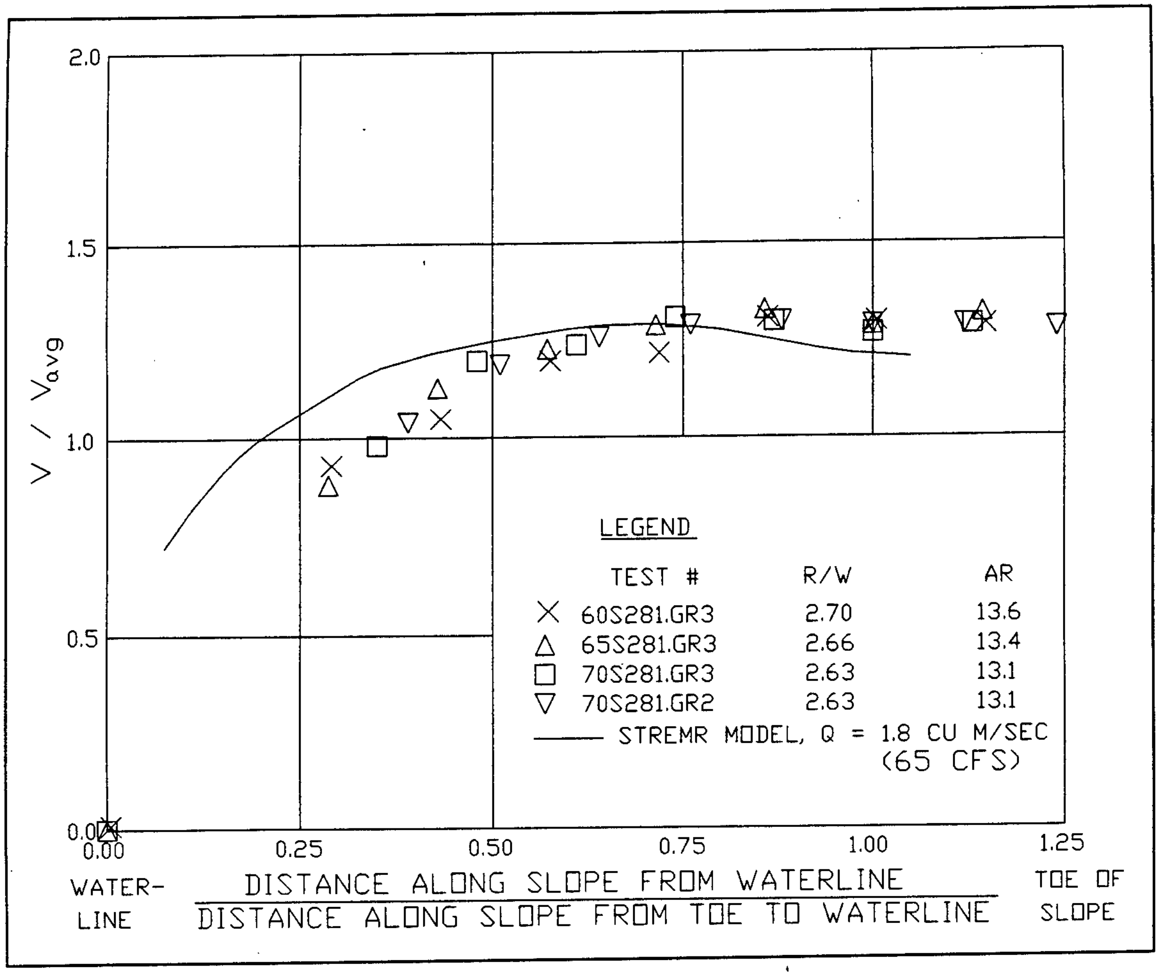


Figure 4. Predicted versus observed velocity, RTF, 1V:2H side slope, station 2+81, discharge 1.7 to 1.9 cu m/sec (60 to 70 cfs)

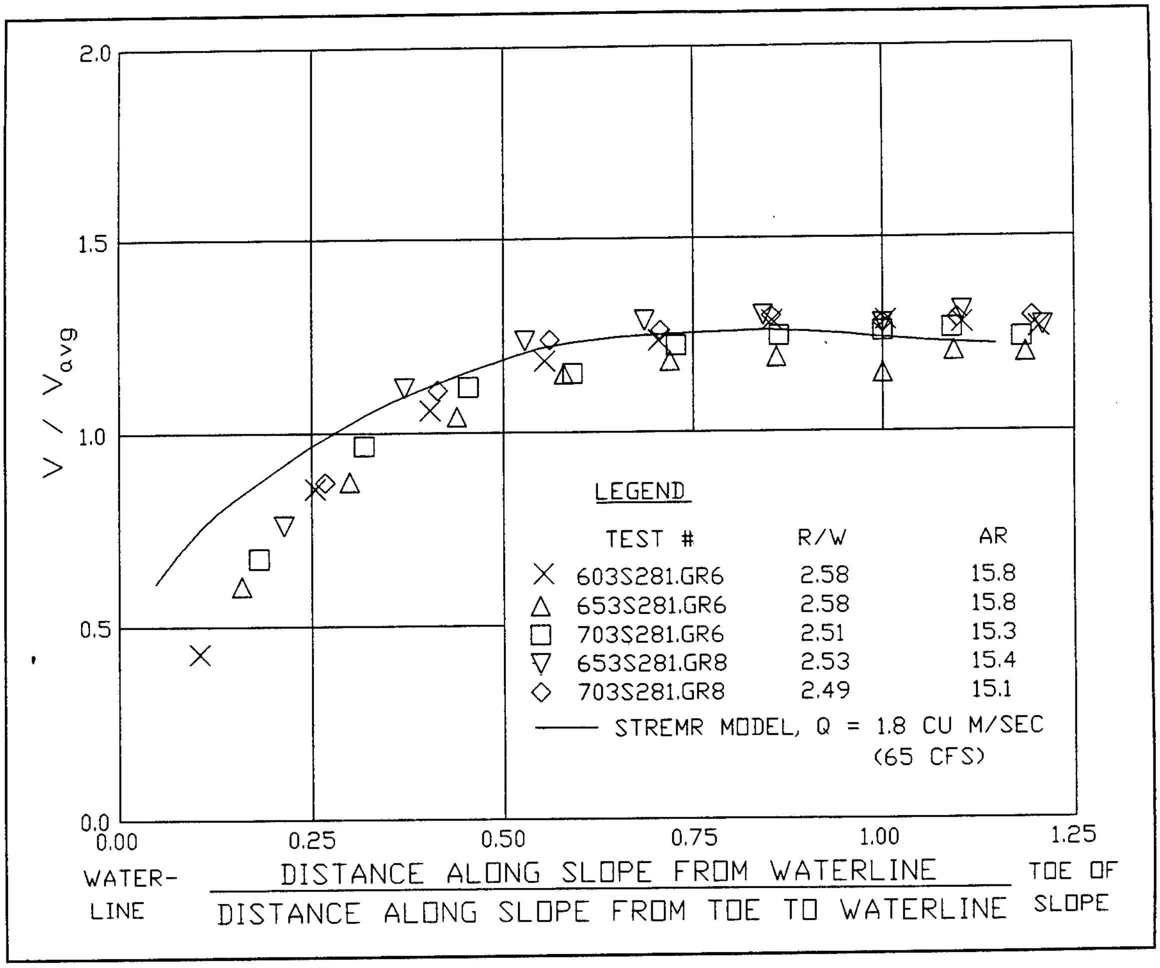


Figure 5. Predicted versus observed velocity, RTF, 1V:3H side slope, station 2+81, discharge 1.7 to 1.9 cu m/sec (60 to 70 cfs)

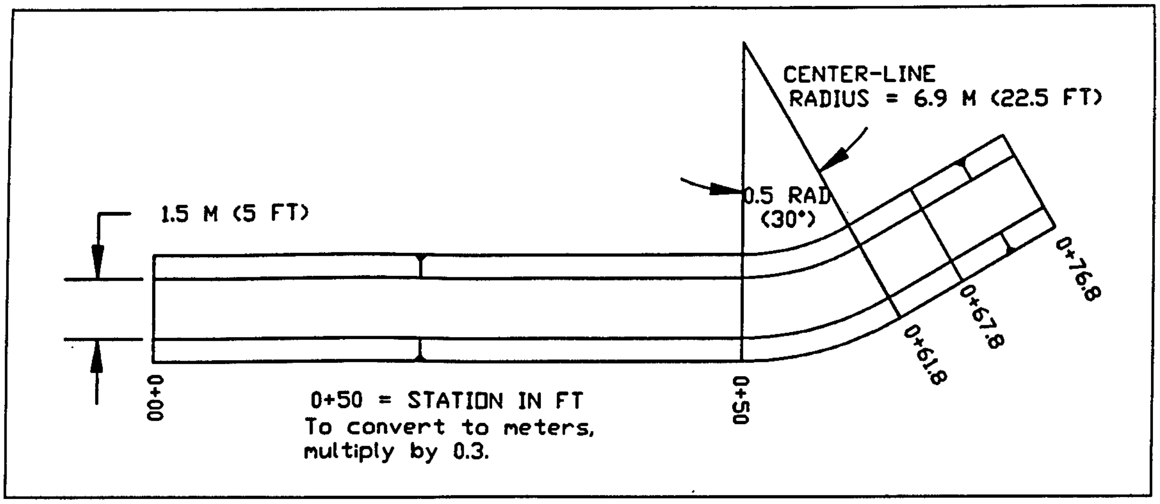


Figure 6. Schematic of 0.5-rad (30-deg) bend

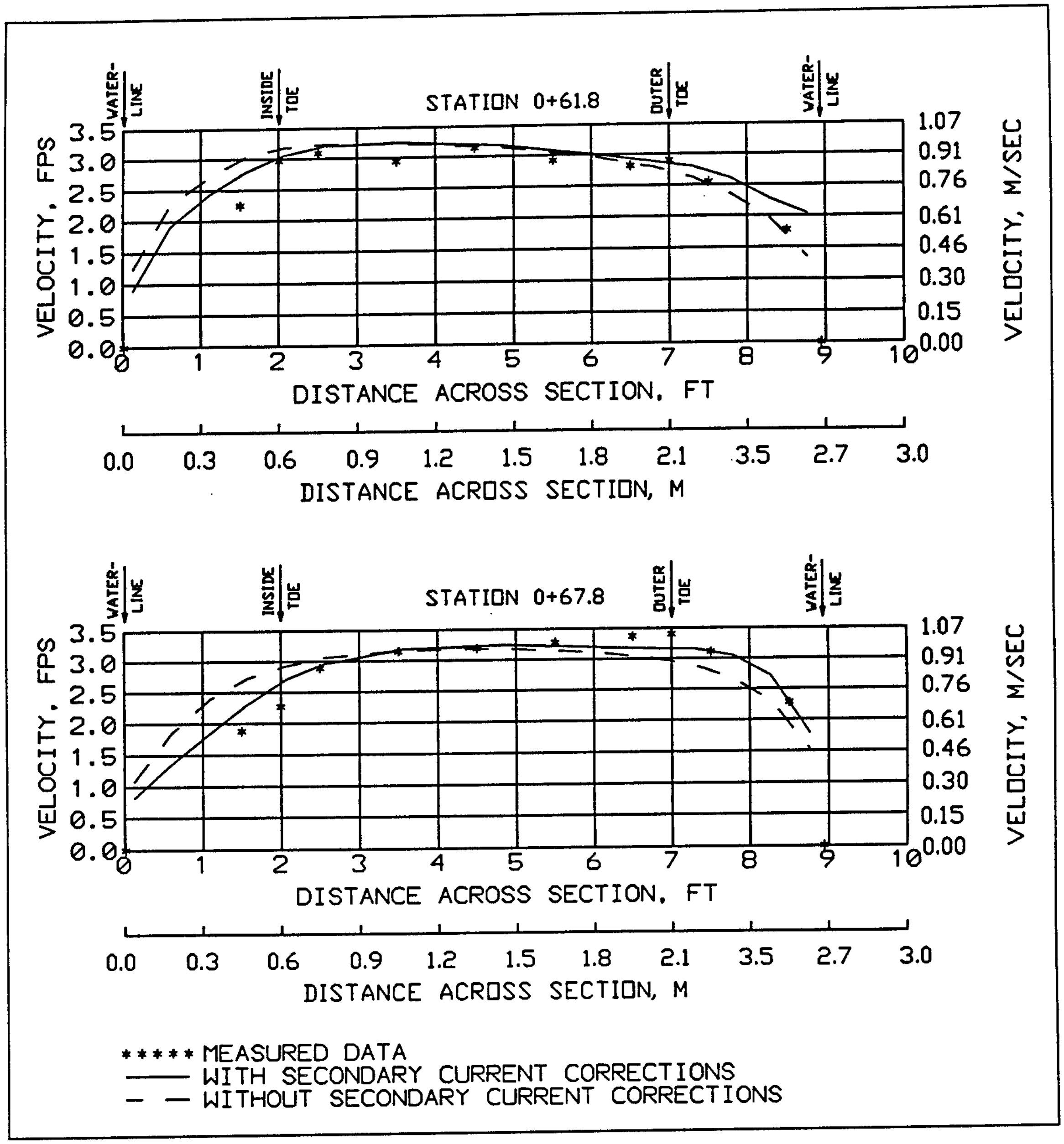
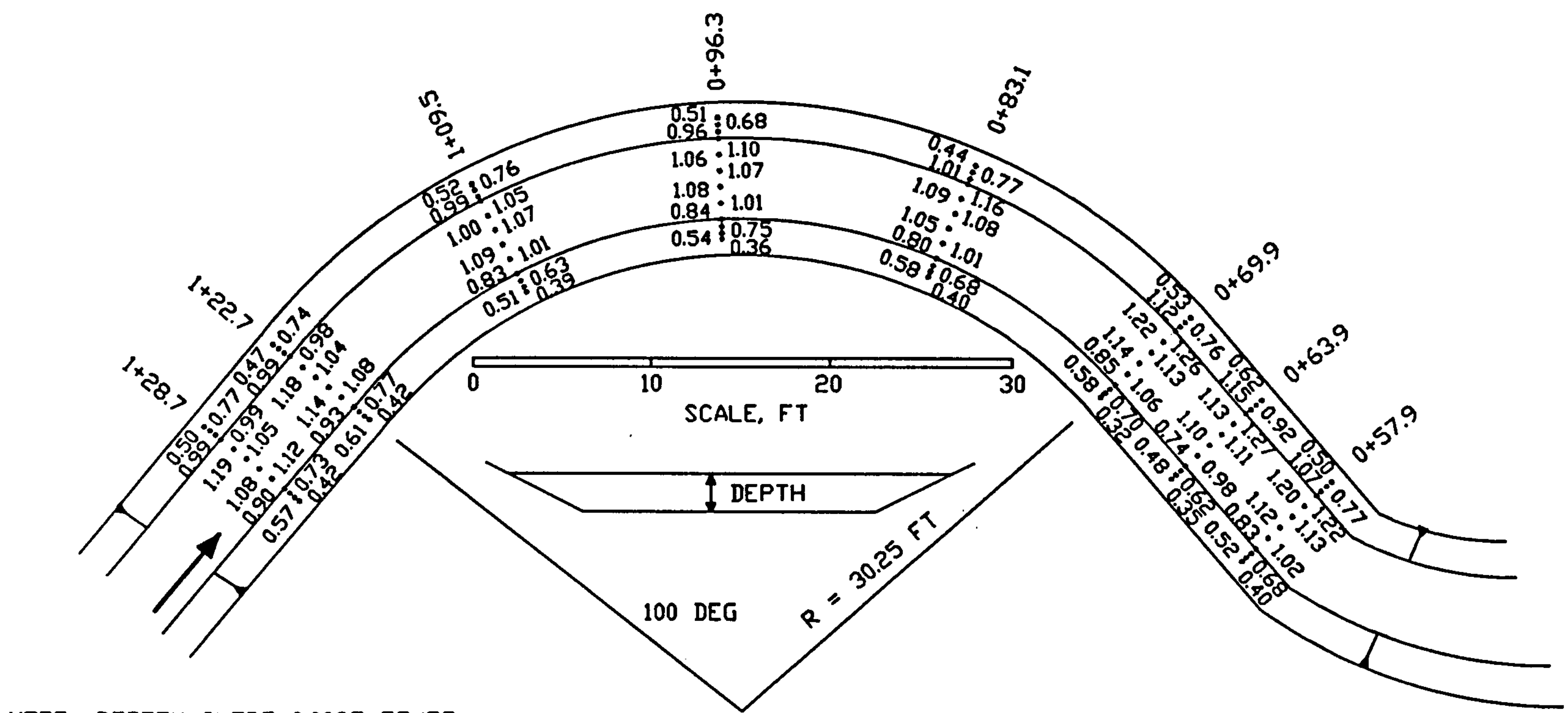


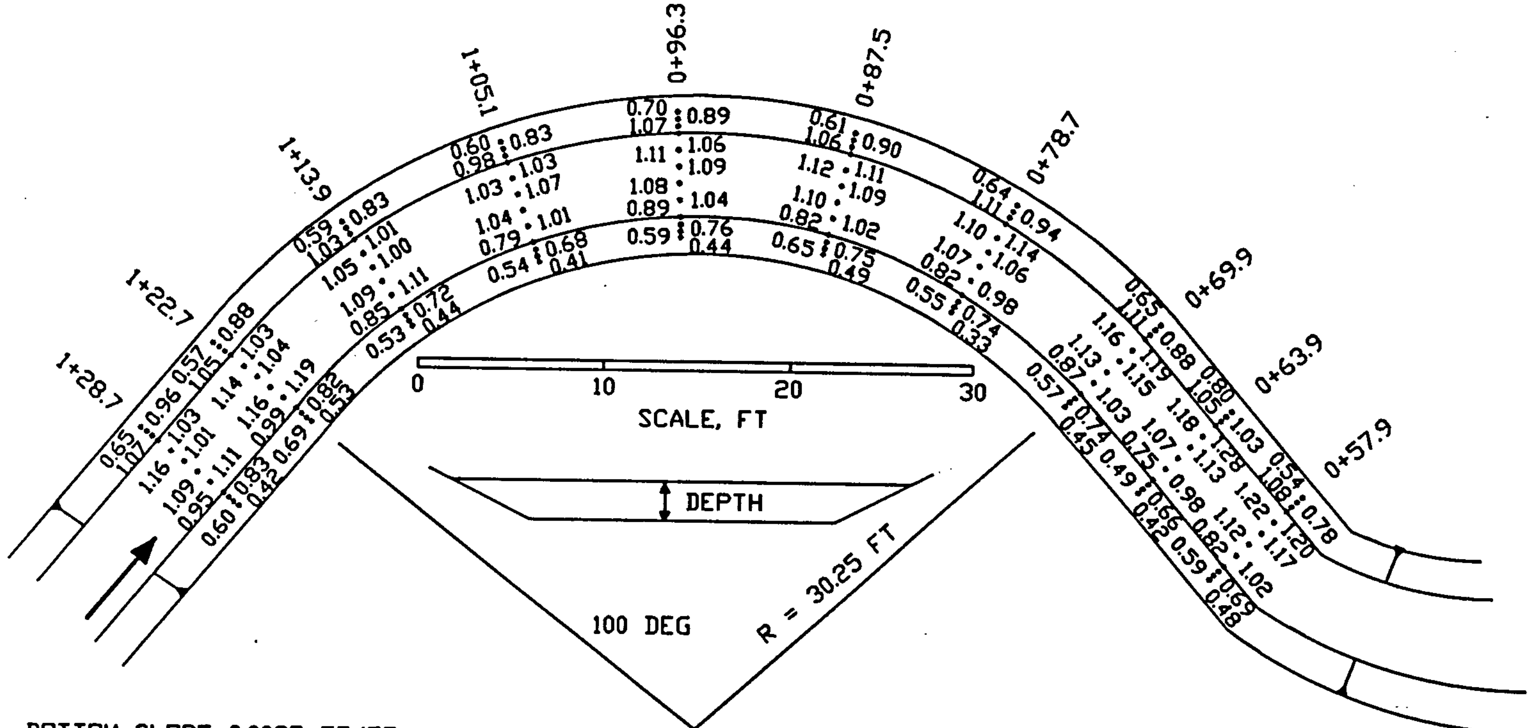
Figure 7. Computed versus measured velocity, 0.5-rad (30-deg) bend



NOTE: BOTTOM SLOPE 0.0025 FT/FT

TRAPEZOIDAL CHANNEL, 1.3 M (4.4 FT) BOTTOM, WIDTH, 1V:2H SIDE SLOPES,
RIPRAP IS 50% #4 - 9.4 MM (3/8"), 50% 9.4 - 12.7 MM (3/8" - 1/2")
SIDE SLOPE VELOCITIES 0.07 M (0.25 FT) APART, BOTTOM VELOCITIES ARE 0.3 (0.88 FT) APART
DEPTH IS AVERAGE DEPTH OVER REACH
1.01 = MEASURED VELOCITY/AVERAGE CHANNEL VELOCITY OVER REACH

Figure 8. Dimensionless velocities, 1.7-rad (100-deg) bend, discharge 0.15 cu m/sec (5.3 cfs), depth 152 mm (0.50 ft)



NOTE: BOTTOM SLOPE 0.0025 FT/FT

TRAPEZOIDAL CHANNEL, 1.3 M (4.4 FT) BOTTOM, WIDTH, 1V:2H SIDE SLOPES,

RIPRAP IS 50% #4 - 9.4 MM (3/8"), 50% 9.4 - 12.7 MM (3/8"-1/2")

SIDE SLOPE VELOCITIES [illegible] M (0.25 FT) APART, BOTTOM VELOCITIES ARE 0.3 M (0.88 FT) APART

DEPTH IS AVERAGE DEPTH OVER REACH

1.01 = MEASURED VELOCITY/AVERAGE CHANNEL VELOCITY OVER REACH

Figure 9. Dimensionless velocities, 1.7-rad (100-deg) bend, discharge 0.16 cu m/sec (5.5 cfs), depth 158 mm (0.52 ft)

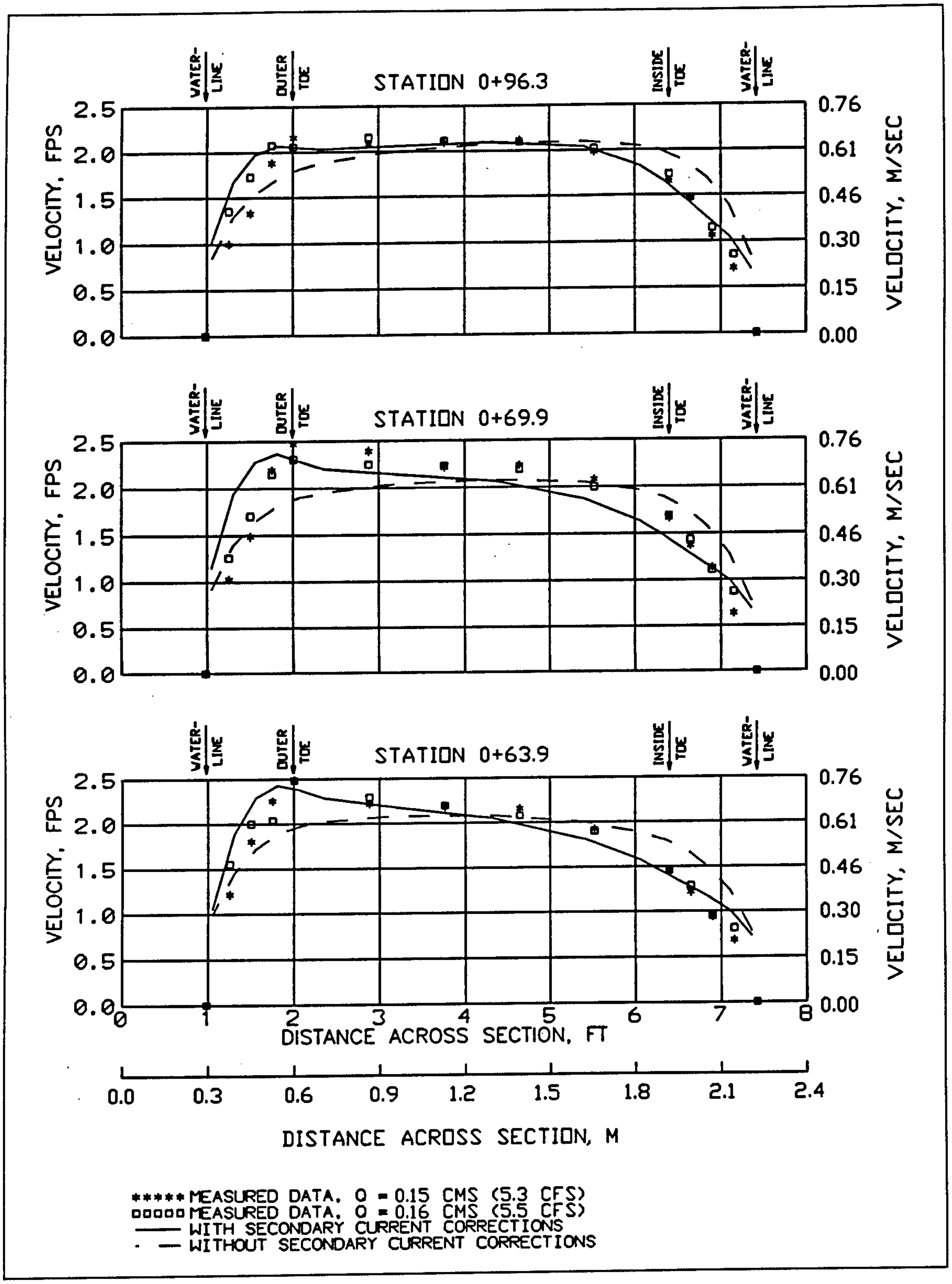


Figure 10. Computed versus measured velocity, 1.7-rad (100-deg) bend

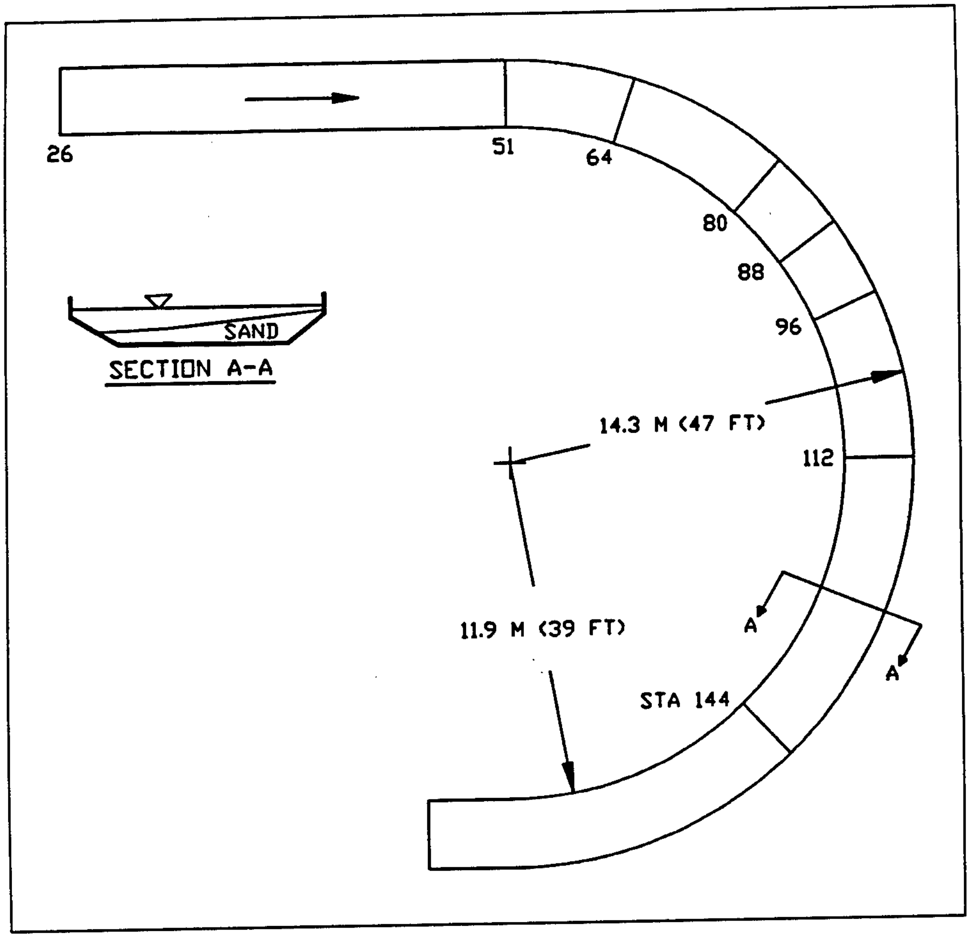


Figure 11. Schematic of 3.1-rad (180-deg) bend

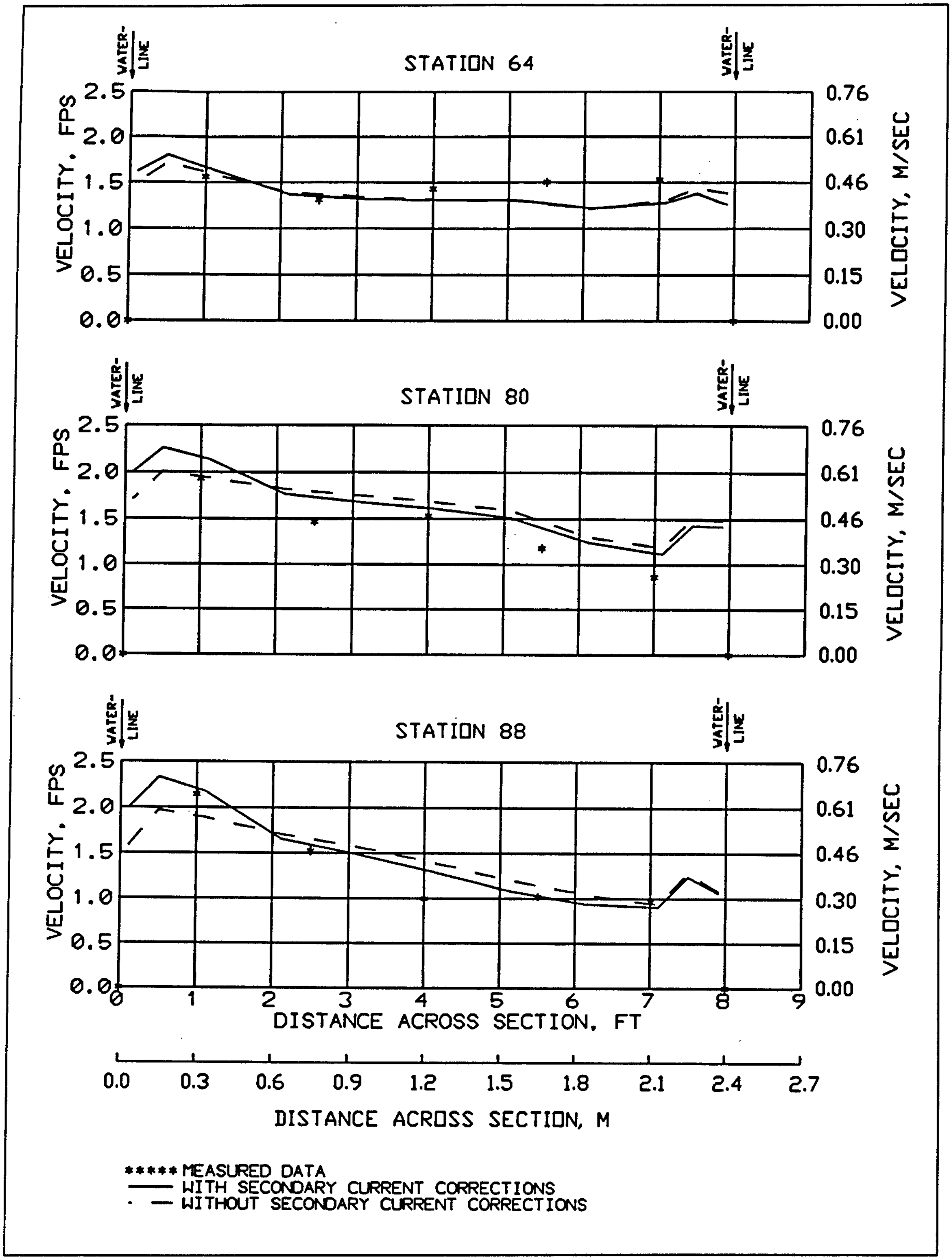


Figure 12. Computed versus measured velocity, 3.1-rad (180-deg) bed (Continued)

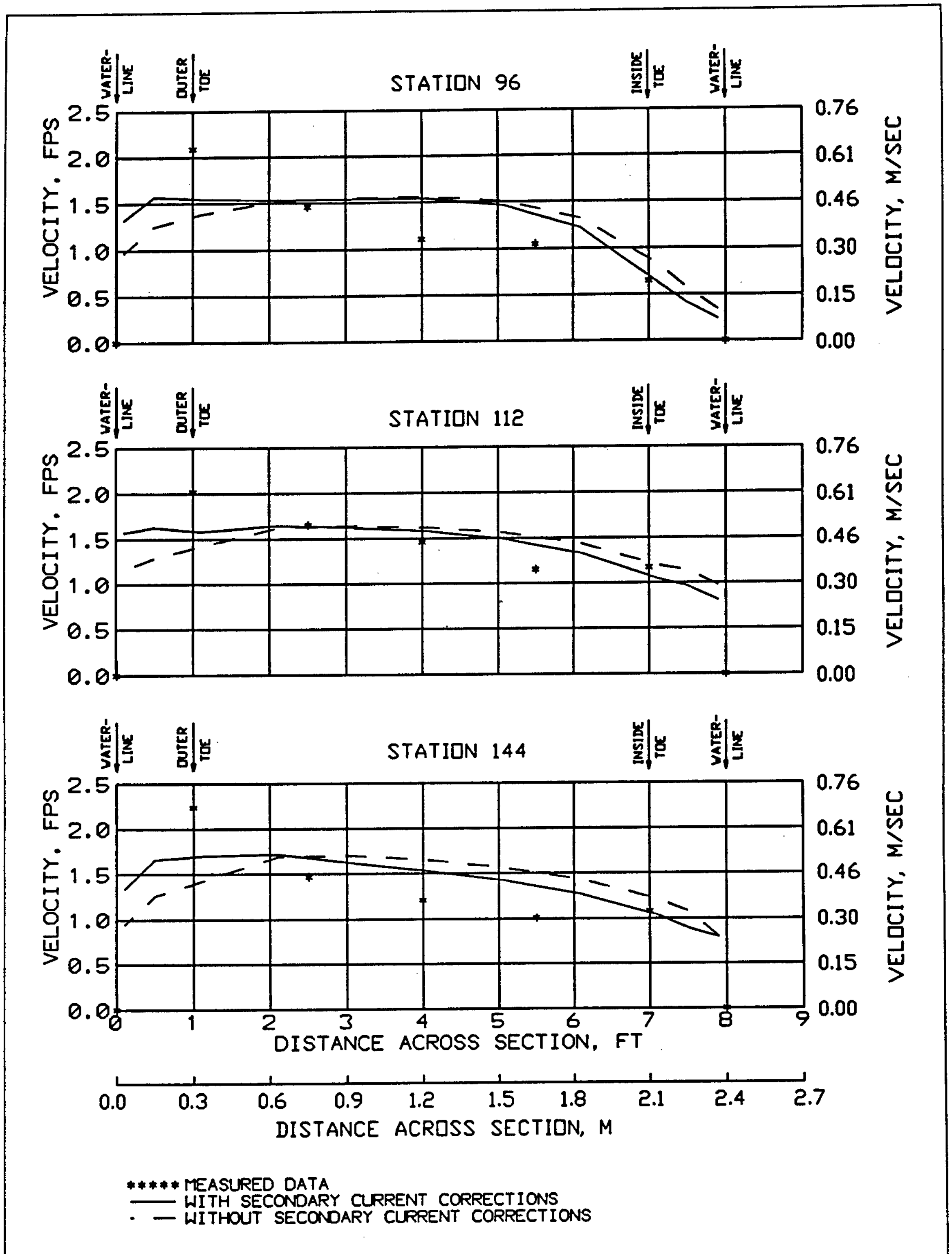


Figure 12. (Concluded)

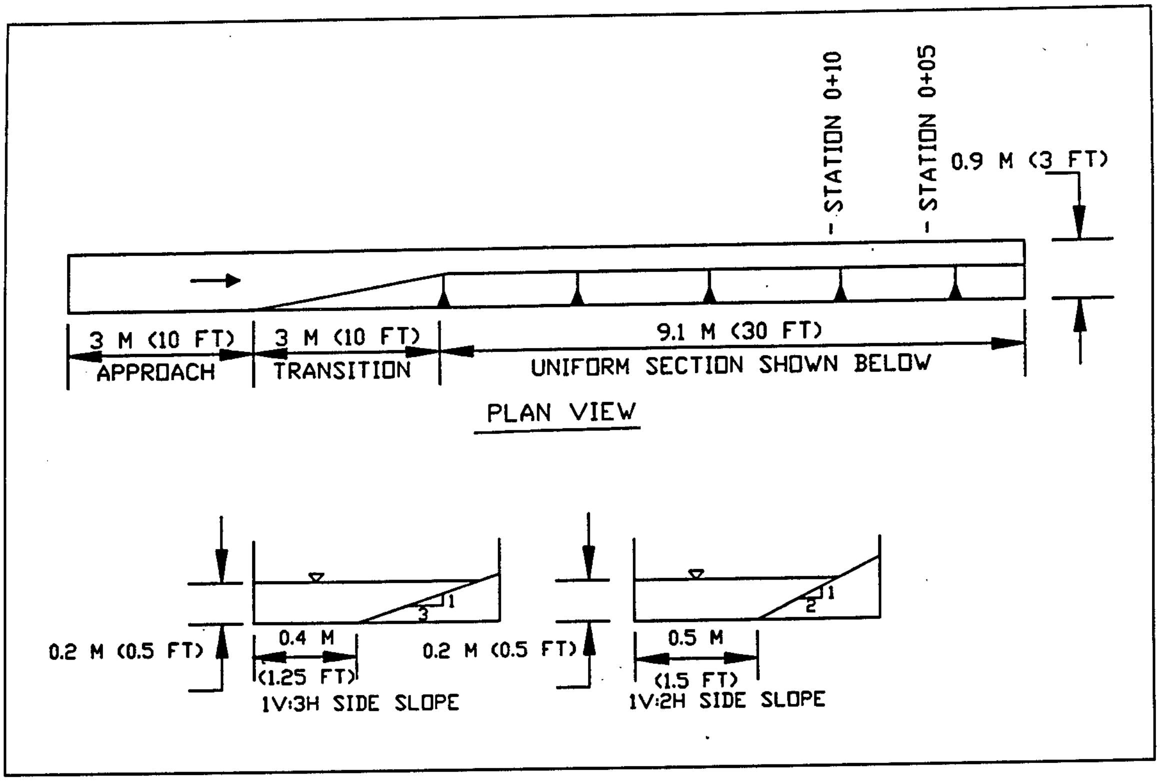


Figure 13. Schematic of straight channel

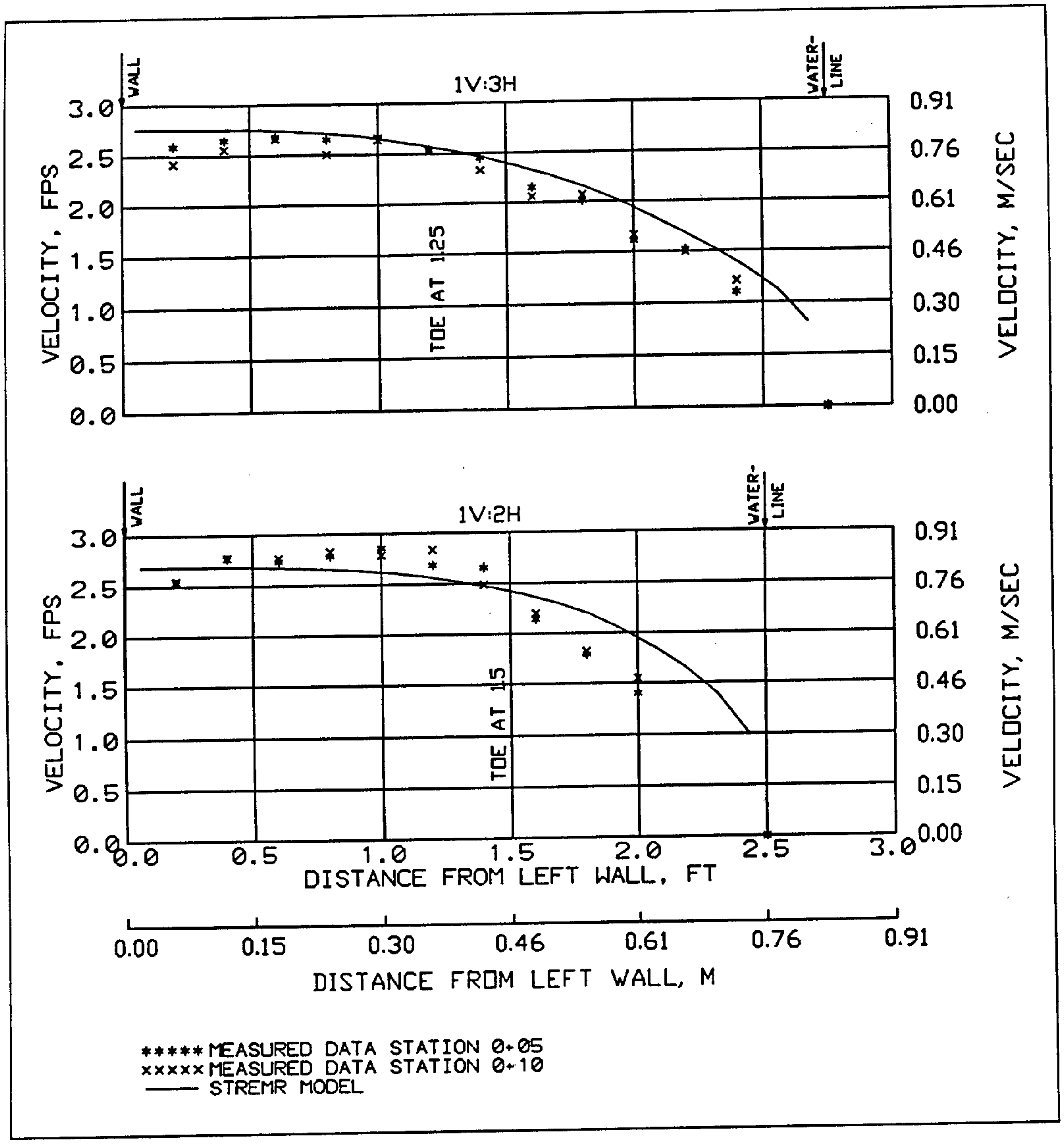


Figure 14. Computed versus measured velocity, straight channel

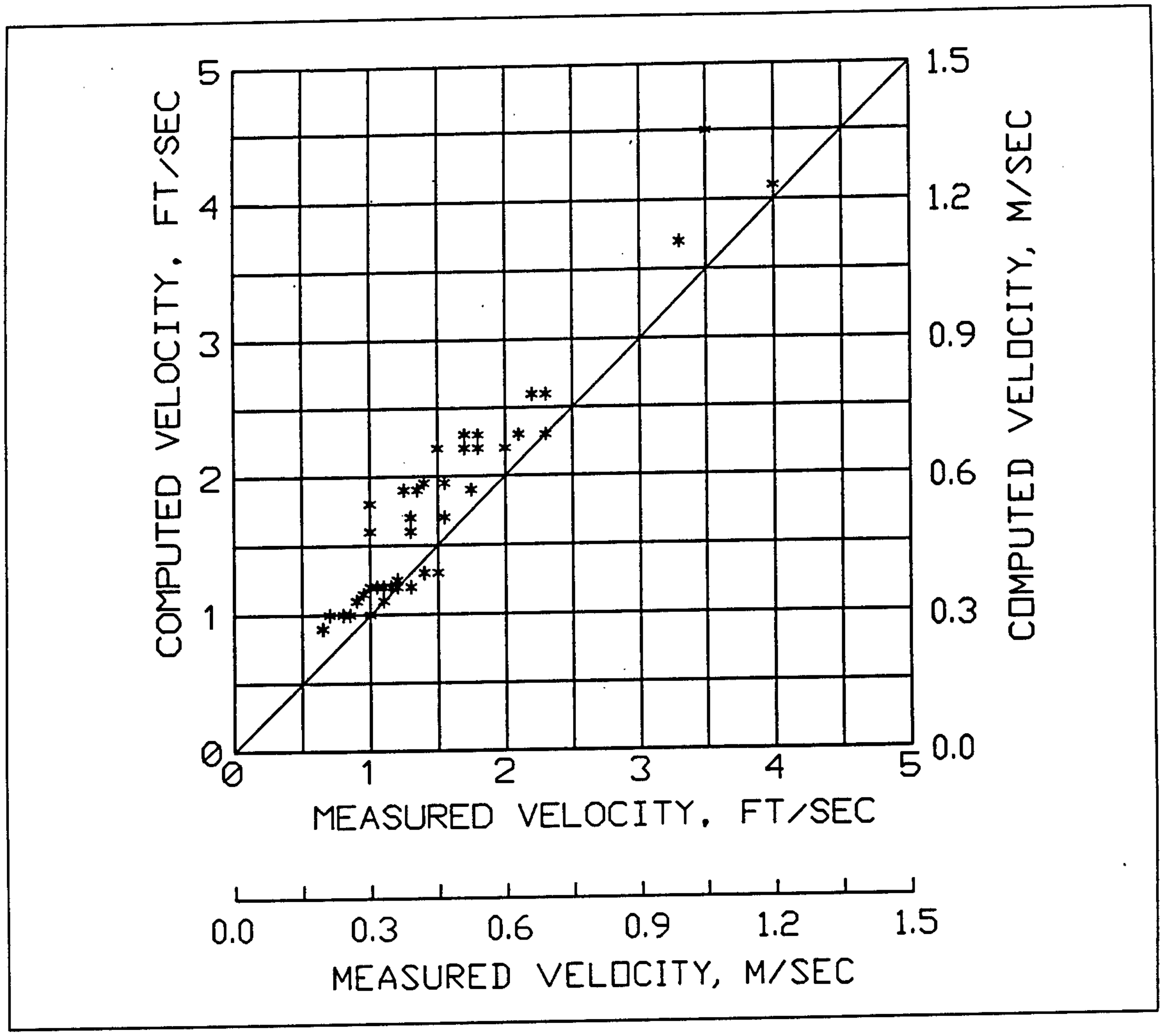


Figure 15. Scatter plot, 1V:2H side slope, upper bank

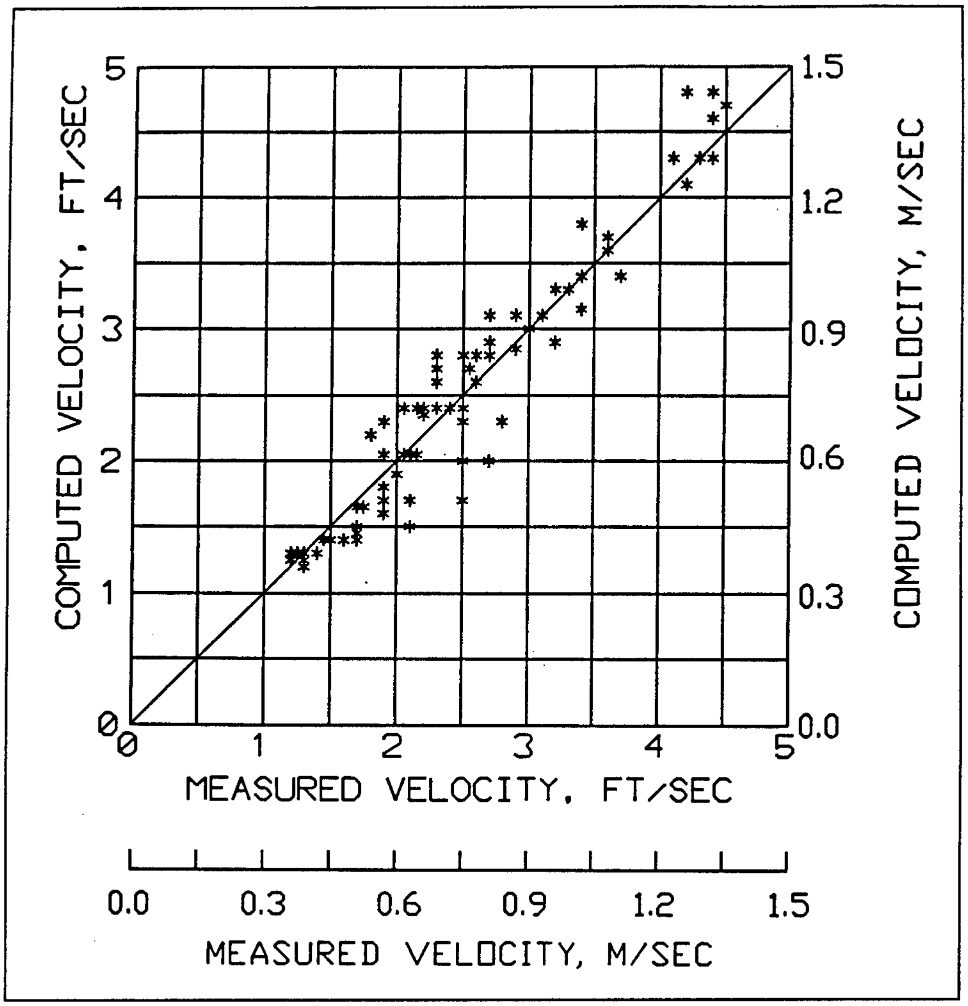


Figure 16. Scatter plot, 1V:2H side slope, lower bank

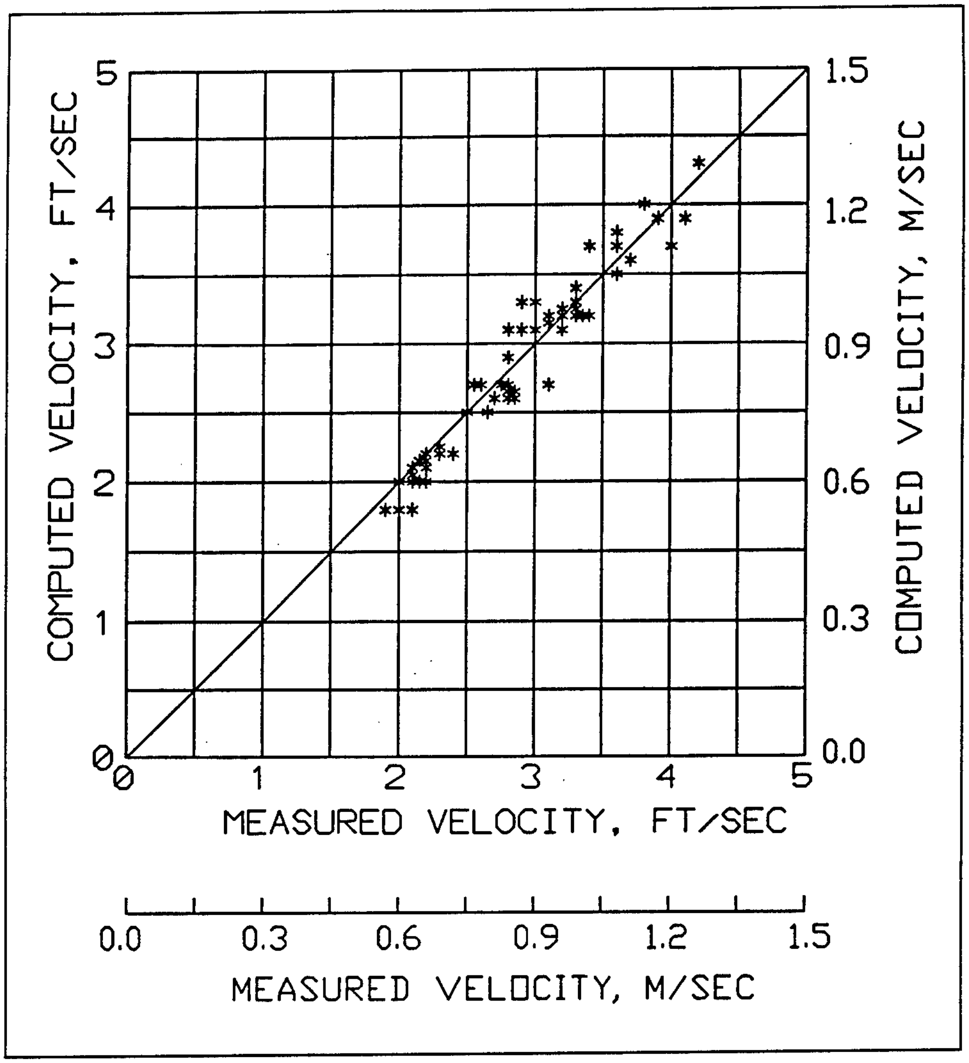
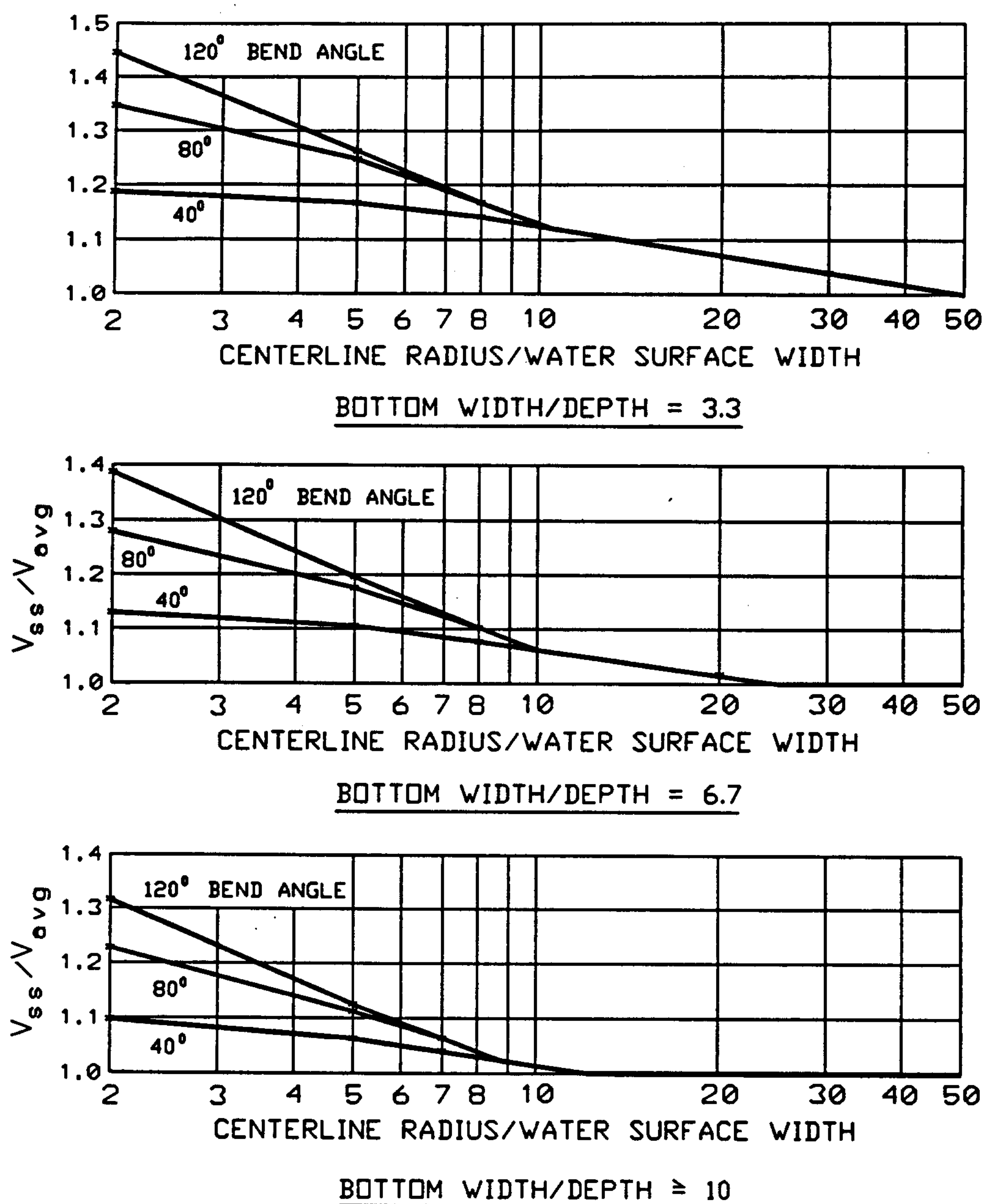


Figure 17. Scatter plot, 1V:2H side slope, channel bottom



NOTE: V_{SS} IS DEPTH-AVERAGED VELOCITY AT 20 PERCENT OF SLOPE LENGTH UP FROM TOE, MAXIMUM VALUE IN BEND

CURVES BASED ON STREMR NUMERICAL MODEL (BERNARD AND SCHNEIDER 1992)

APPLICABLE TO 1V:1.5H TO 1V:3H SIDE SLOPES

$n/(\text{MAXIMUM DEPTH})^{1/6} \leq 0.026$

Figure 18. Riprap design velocities, trapezoidal channel

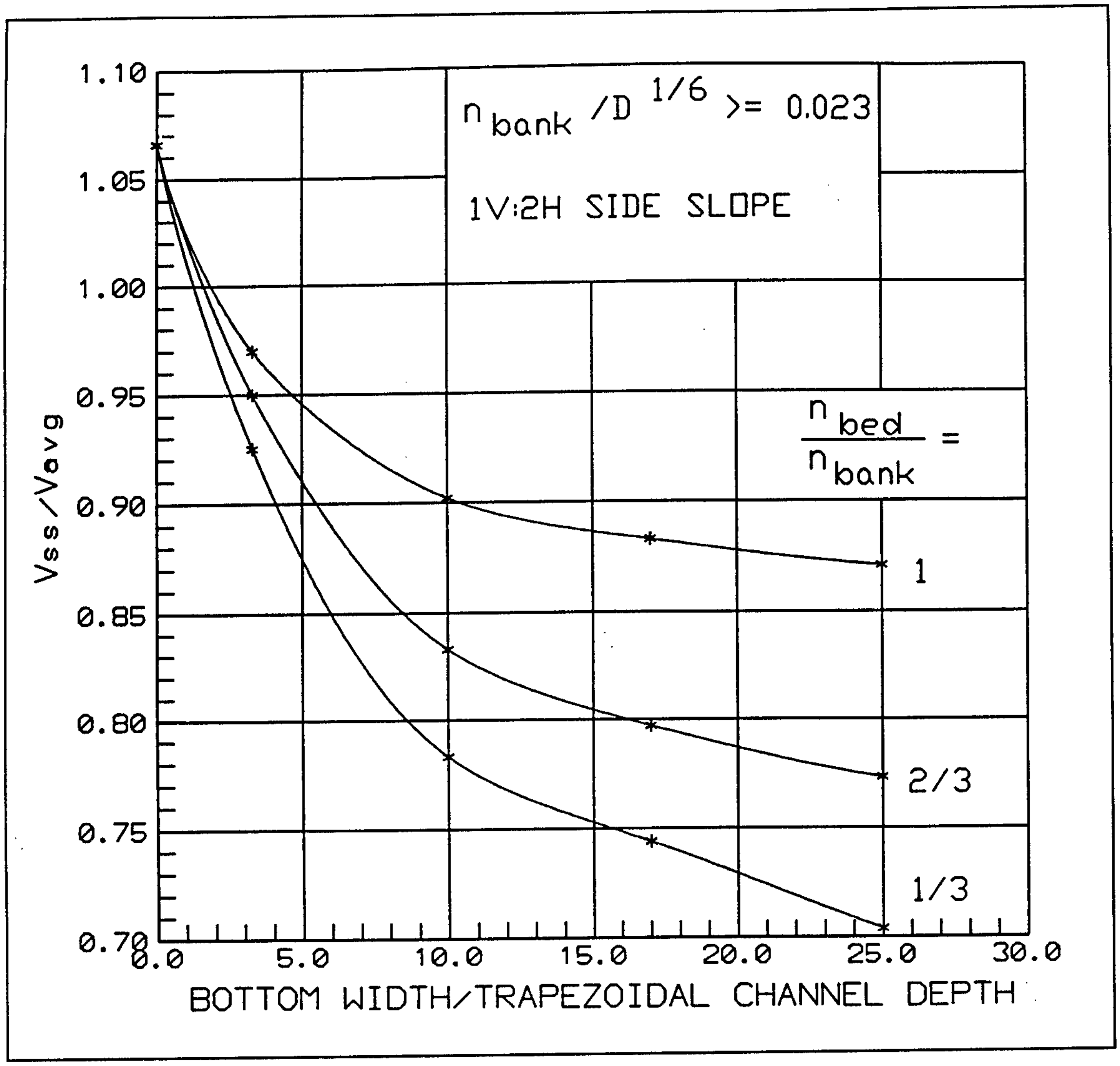


Figure 19. Nomograph for determining V_{ss}/V_{avg} in straight channels. Channel must not be close to upstream bends or other features causing a skewed velocity distribution

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13.ABSTRACT *(Maximum 200 words)*
The STREMR two-dimensional depth-averaged model is compared to observed data from three trapezoidal channel bends, one straight trapezoidal channel, and one natural channel bend having an erodible bed. STREMR was selected because it includes an empirical correction for secondary currents. Without the secondary correction activated, STREMR did poorly in channel bends. With the secondary correction activated, the model did well on the channel bottom and on the lower half of the side slope. Predicted velocities were greater than observed velocities on the upper half of the side slope. The secondary correction in natural channels is needed but less significant than in trapezoidal channels because natural channel bathymetry plays a significant role in defining velocity distribution.

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Appendix A
Notation

g	Gravitational constant
MAE	Mean absolute error
MRE	Mean relative error
MTE	Mean trend error
n	Manning's resistance coefficient
N	Number of data points
R	Center-line radius of bend
RTF	Riprap Test Facility
S	Distance along slope from toe to waterline
V	Depth-averaged velocity
V_{avg}	Average channel velocity
V_c	Computed velocity
V_m	Measured velocity
V_{ss}	Depth-averaged velocity at 20 percent of the slope length up from the toe
W	Water-surface width
Δh	Superelevation (inside elevation - outside elevation)